Constraining dense-matter superfluidity through thermal emission from millisecond pulsars

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ABSTRACT

As a neutron star spins down, the gradual decrease of the centrifugal force produces a progressive increase of the density of any given fluid element in its interior. Since the "chemical" (or "beta") equilibrium state is determined by the local density, this process leads to a chemical imbalance quantified by a chemical potential difference, e.g., $\delta\mu \equiv \mu_n - \mu_p - \mu_e$, where n, p, and e denote neutrons, protons, and electrons. In the presence of superfluid energy gaps, in this case Δ_n and Δ_p, reactions are strongly inhibited as long as both $\delta\mu$ and kT are much smaller than the gaps. Thus, no restoring mechanism is available, and the imbalance will grow unimpeded until $\delta\mu = \delta\mu_{thr} \sim \Delta_n + \Delta_p$. At this threshold, the reaction rate increases dramatically, preventing further growth of $\delta\mu$, and converting the excess chemical energy into heat. The thermal luminosity resulting from this "rotochemical heating" process is $L \sim 2 \times 10^{-4}(\delta\mu_{thr}/0.1\,\mathrm{MeV})\dot{E}_{rot}$, similar to the typical x-ray luminosity of pulsars with spin-down power $\dot{E}_{rot}$. The threshold imbalance, and therefore the luminous stage, are only reached by stars whose initial rotation period is $P_i \lesssim 12(\delta\mu_{thr}/0.1\,\mathrm{MeV})^{1/2}$ ms, i.e., millisecond pulsars. A preliminary study of eleven millisecond pulsars with reported ROSAT observations shows that the latter can already be used to start constraining superfluid energy gaps in the theoretically interesting range, $\sim 0.1 - 1\,\mathrm{MeV}$.

Subject headings: dense matter — equation of state — stars: neutron — pulsars: general — ultraviolet: stars — X-rays: stars

1. Introduction

The precise timing of radio pulsars allows an excellent determination of neutron star rotation periods, P, and their (positive) time derivatives, $\dot{P}$, which in turn yield the characteristic time scales for spin-down, $t_s \equiv P/(2\dot{P}) \sim 10^3 - 10^{10}\,\mathrm{yr}$ (Taylor, Manchester, & Lyne 1993). At least some of these objects are born in supernova explosions, after which they are hot ($T \sim 10^{11}\,\mathrm{K}$) and spin with periods of a few tens of milliseconds. Standard models of cooling through neutrino and photon emission leave neutron stars with negligible internal heat after $\sim 10^7\,\mathrm{yr}$ (Nomoto & Tsuruta 1987; Page & Applegate 1992), while they gradually spin down.

Millisecond pulsars are faster ($P \sim 1.5 - 10\,\mathrm{ms}$), older ($t_s > 10^8\,\mathrm{yr}$), and less magnetized (with surface magnetic field strengths $B \sim 10^{8-9}\,\mathrm{G}$) than ordinary pulsars, and usually have binary companions, most often cool white dwarfs (Phinney & Kulkarni 1994). This combination of properties has led to the suggestion that these stars have been "recycled" through accretion from a binary companion, which gave them additional angular momentum and, perhaps, reduced their magnetic field (Bisnovatyi-Kogan & Komberg 1975; Bhattacharya & van den Heuvel 1991). The temperatures of the white dwarf companions, when compared with cooling models, provide an independent age estimate, t_c, which tends to be smaller than t_s, though not by a large factor (Kulkarni 1986; Bell, Bailes, & Bessell 1993; Lorimer et al. 1995; Bell et al. 1995; Alberts et al. 1996; Lundgren et al. 1996a; Lundgren, Foster, & Camilo 1996b). This confirms that these are old systems, in which *the pulsar has already lost a considerable amount of rotational energy* (similar or somewhat smaller than that which it currently carries) *and essentially all the thermal energy it originally contained.*

Neutron star cores are usually assumed to contain neutrons, protons, electrons, in the denser central region also muons, and possibly other kinds of particles. More exotic possibilities, such as "free" quark cores or even "strange stars" composed exclusively of a mixture of u, d, and s quarks not confined into hadrons (plus a small admixture of electrons) also cannot be excluded at present.

Within the standard scenario, it was proposed decades ago that both neutrons and protons should form Cooper pairs (bound by strong interactions) and undergo a *superfluid transition* at a still very uncertain temperature $T_c \sim 10^{9-10}\,\mathrm{K}$ (Migdal 1960; Ginzburg & Kirzhnits 1965; Sauls 1989), much lower than the nucleon Fermi temperatures $T_F \sim 10^{12}\,\mathrm{K}$, but higher than temperatures expected inside observed neutron stars ($T \lesssim 10^8\,\mathrm{K}$), and particularly in ms pulsars. In spite of the long and distinguished history of interest in the subject, there has been little observational evidence for it, mostly limited to glitch dynamics, which is interpreted in terms of pinning and unpinning of neutron superfluid vortices to the solid lattice in the inner crust (Pines & Alpar 1985).

In the superfluid state, the density of quasiparticle states as a function of energy has a *gap* between $E_F - \Delta$ and $E_F + \Delta$, where E_F is the Fermi energy and Δ is the gap parameter (Tilley & Tilley 1990). Neutrons in the stellar crust and protons in the core are expected to have an isotropic gap (with $\Delta \approx 1.76kT_c$ at $T = 0$) like that in laboratory superconductors, whereas core neutrons should have a more complicated, anisotropic gap (Amundsen & Østgaard 1985). At low temperatures, $kT \ll \Delta$, the number of occupied states above the gap and that of empty states below it are proportional to $\sim \exp(-\Delta/kT)$, which suppresses the heat capacity and the equilibrium reaction rates by similar factors (Levenfish & Yakovlev 1992a,b), strongly affecting the thermal evolution of neutron stars. There have been attempts to use x-ray observations of cooling neutron stars to constrain the energy gaps (Page & Applegate 1992; Page 1994, 1995), but so far the results are not very conclusive (Page 1996).

In this paper, I discuss how the presence of superfluid energy gaps delays and enhances the recently proposed process of *"rotochemical heating"* (Reisenegger 1995; hereafter R95), leading to *substantial thermal emission from ancient millisecond pulsars.* The presence or absence of this emission can therefore be used to constrain the value of the gaps. The next section describes the physical model, which is applied to observational data in §3 to obtain preliminary constraints. In §4 the results are discussed and improvements are suggested.

2. The model

The fast rotation rate, $\Omega = 2\pi/P$, of ms pulsars produces a strong centrifugal force, which reduces their internal density by $\Delta\rho/\rho \approx -\alpha\Omega^2/(2G\rho_c)$ with respect to its nonrotating value. (Here, ρ_c is the central density, G is the constant of gravity, and α is a

dimensionless number of order unity [R95]). *Their spin-down causes a slow contraction.* The relative abundances of different particle species in reaction equilibrium in the stellar core depend on the density, and therefore *the contraction gives rise to a "chemical" imbalance*, whose effect on the thermal evolution has been considered for the cores of neutron stars (R95) and strange stars (Cheng & Dai 1996), as well as for neutron star crusts (Iida & Sato 1996), in all cases without superfluidity. In most of this section, I concentrate on neutron star cores of standard composition (neutrons, protons, and electrons), in which direct Urca reactions ($n \to p+e+\bar{\nu}_e$ and $p+e \to n+\nu_e$) are allowed (Lattimer et al. 1991), and in which *the neutrons, the protons, or both are in the superfluid state*, with gap parameters Δ_n and Δ_p. Alternatives are discussed below.

The chemical imbalance can be quantified by $\delta\mu = \mu_n - \mu_p - \mu_e$, where μ_i are the chemical potentials ($\approx$ Fermi energies) of the three particle species ($i = n, p, e$; note the opposite sign convention than in R95). In non-superfluid matter, the diffusion of charged particles with respect to the neutrons is limited by proton-neutron collisions, with mean free time $\tau_{pn} \sim 3 \times 10^{-17} T_8^{-2}$ s (Yakovlev & Shalybkov 1990), where $T_8 \equiv T/10^8$ K. The time scale for protons moving at their Fermi velocity, $v_{Fp} \sim 0.2c$, to diffuse a neutron star radius, $R \sim 10$ km, is $t_{pd} \sim (R/v_{Fp})^2 \tau_{pn}^{-1} \sim 30 T_8^2$ yr, much shorter than the evolutionary time scale of a ms pulsar, $t_s \gtrsim 10^8$ yr. This inequality is likely to become even stronger (or at least not much weaker) if superfluid matter is considered instead. Thus, the stellar core can be regarded as being in *diffusive equilibrium*, with $\delta\mu$ constant throughout the stellar core.

The reactions are suppressed by the superfluid energy gap(s), so $|\delta\mu|$ can at first freely grow as $\dot{\delta\mu} = -\alpha(q - 1/3)\mu_e \Omega\dot{\Omega}/(G\rho_c)$, where q is another parameter of order unity, defined as the logarithmic derivative of the symmetry energy with respect to density (see R95 for details). For definiteness, I will assume in the following discussion that $q > 1/3$, so that the contraction produces a neutron excess and a positive $\delta\mu$. As shown schematically in Figure 1, substantial reactions are only "turned on" once $\mu_n - \Delta_n \approx \mu_p + \Delta_p + \mu_e$, i.e. when a neutron just below the neutron energy gap is energetically allowed to decay into a proton just above the proton energy gap, an electron close to the Fermi sphere, and an antineutrino of arbitrarily small en-

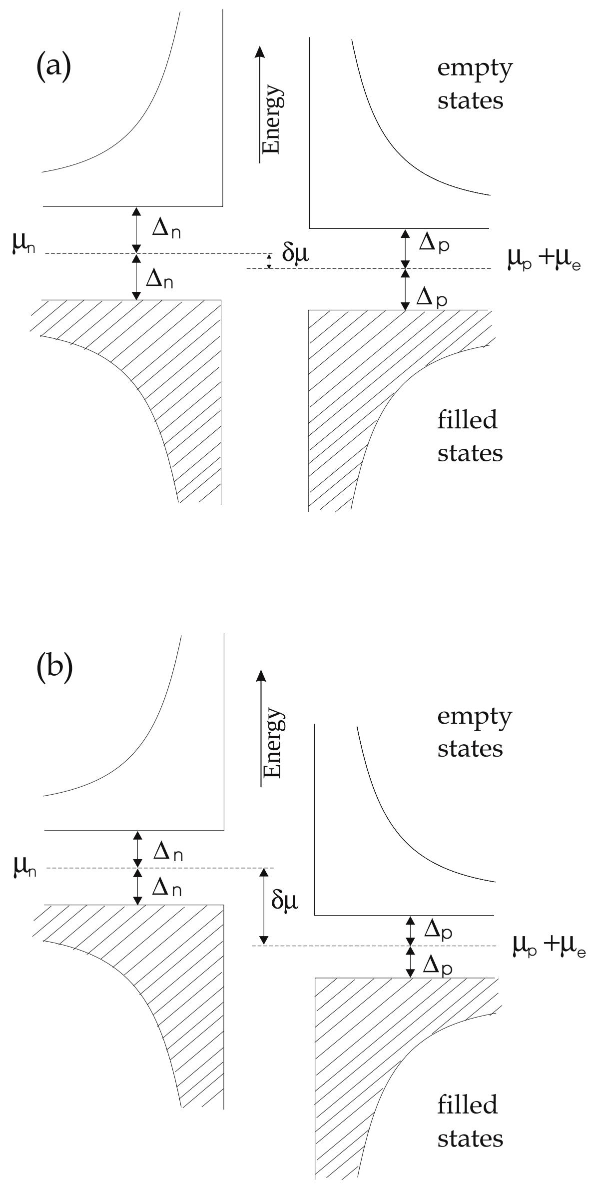

Fig. 1.— Schematic representation of the condition for the occurrence of neutron beta decays (direct Urca). (a) $\delta\mu < \delta\mu_{thr} = \Delta_n + \Delta_p$: Reactions not allowed. (b) $\delta\mu > \delta\mu_{thr} = \Delta_n + \Delta_p$: Reactions allowed.

ergy. Once this threshold, $\delta\mu_{thr} \approx \Delta_n + \Delta_p$, is exceeded in some region of the star (and for some spatial direction, if one or both of the gaps are anisotropic), the reaction rate in that region increases rapidly, preventing further growth of $\delta\mu$. The threshold value is reached once the star has lost a rotational energy $\Delta E_{rot} \approx 1.4 \times 10^{50}(\delta\mu_{thr}/0.1\,\mathrm{MeV})\,\mathrm{ergs}$ (assuming a moment of inertia $I = 10^{45}\,\mathrm{g\,cm^2}$), i.e., the total rotational energy of a star rotating with $P \sim 12(\delta\mu_{thr}/0.1\,\mathrm{MeV})^{-1/2}\,\mathrm{ms}$. Therefore, only ms pulsars are likely to ever reach this stage.

At all later times, the reaction rate is very nearly as needed to keep the imbalance at threshold, $\delta\mu = \delta\mu_{thr}$, and each reaction leaves a thermal energy $\approx \delta\mu_{thr}$ in the stellar core, with a much smaller amount escaping as neutrinos. The thermal energy must eventually reach the surface of the star and be radiated as thermal photons, with a bolometric luminosity

$$L \sim \alpha(3q-1)xN\delta\mu_{thr}\,\frac{1-2x}{1+4x}\,\frac{\Omega\dot{\Omega}}{G\rho_c}, \qquad (1)$$

where N is the total number of baryons in the star, and x is the proton fraction ($x > 1/9$ for direct Urca reactions to be allowed). L is conveniently expressed as a fraction of the total spin-down power, i.e., the rotational energy loss per unit time, $\dot{E}_{rot} = I\Omega\dot{\Omega}$. For typical parameter values (see R95), $L/\dot{E}_{rot} \sim 2 \times 10^{-4}(\delta\mu_{thr}/0.1\,\mathrm{MeV})$.

If $x < 1/9$, so that direct Urca reactions are forbidden by simultaneous energy and momentum conservation, the dominant reactions are modified Urca reactions, in which an additional particle participates (via strong interactions), carrying off the excess momentum (Chiu & Salpeter 1964). As long as no other hadrons are present, this extra particle will be a neutron or a proton, whichever has the smaller energy gap, $\Delta_<$, and the threshold chemical imbalance becomes $\delta\mu_{thr} \approx \Delta_n + \Delta_p + 2\Delta_<$. Otherwise, the discussion given for direct Urca processes goes through unchanged. For modified Urca processes mediated by other particles, such as kaons or pions (where $\delta\mu_{thr}$ should be as in the direct Urca case), and in quark matter (where superfluid quarks may take the place of the superfluid nucleons), the effect should also be similar, but with a somewhat later onset, due to the more homogeneous composition of the stellar core.

For comparison, the steady-state luminosity of non-superfluid neutron stars is given by $L/\dot{E}_{rot} \sim 4 \times 10^{-5}(\dot{E}_{rot}/3 \times 10^{33}\,\mathrm{ergs\,s^{-1}})^{1/7}\,\mathrm{MeV}$ if only modified Urca reactions are allowed, and much lower if fast cooling processes are present (R95). Thus, superfluid and non-superfluid neutron stars should be easily distinguishable by this effect.

The whole discussion above is based on the assumption that the particle species in the stellar core can only achieve chemical equilibrium by reactions occuring inside the core. However, as said above, the particles can easily move throughout the star on time scales much shorter than the evolutionary times of ms pulsars. Thus, parts of any neutron excess in the core can easily flow into the crust, where they can be absorbed by nuclei. This process is opposite to the neutron emission and absorption by nuclei in the inner crust as its density changes due to the spin-down process (Iida & Sato 1996). However, since many more neutrons are available in the core than in the crust, the former are likely to dominate and completely change the nuclear chemistry in the inner crust. Depending on the time scales and thresholds for the relevant nuclear transformations in the crust, this process may provide a shortcut for the chemical equilibration and prevent the imbalance from growing as much as assumed in the previous sections and in R95. This is clearly a subject that deserves more study.

3. Application to observational data

In this section, I make a preliminary analysis of the data available in the literature for eleven millisecond pulsars observed (but in most cases not detected) in the soft x-rays by ROSAT (Kulkarni et al. 1992; Fruchter et al. 1992; Becker & Trümper 1993; Danner, Kulkarni, & Thorsett 1994; Halpern, Martin, & Marshall 1996; Halpern 1996; Becker et al. 1996; Verbunt et al. 1996)[1], in order to show how the threshold chemical imbalance, $\delta\mu_{thr}$, can be constrained by observations. Given the limitations of the present study (discussed in detail below), any given limit determined here should not be taken too seriously, but their combination gives an indication of what could be done.

For pulsars that have *not* yet reached $\delta\mu_{thr}$, the chemical disequilibrium at the present time can be approximated by

[1] I omit PSR B1620-21 from the analysis since no intrinsic period derivative, $\dot{P}$, is available for it.

$$\delta\mu \approx \delta\mu_1 \equiv 18 \left(\frac{P}{\mathrm{ms}}\right)^{-2} \frac{t}{t_s - t}\,\mathrm{MeV} \lesssim \delta\mu_{thr}, \quad (2)$$

where t is the true age of the pulsar (more precisely, the time since it left the chemical equilibrium state), and magnetic dipole braking ($\dot{\Omega} \propto -\Omega^3$) has been assumed. Alternatively, if the threshold value *has* been reached,

$$\delta\mu = \delta\mu_{thr} \lesssim \delta\mu_2 \equiv 500 \frac{L}{\dot{E}_{rot}}\,\mathrm{MeV}, \quad (3)$$

where L is the bolometric luminosity of the pulsar, and the inequality allows for additional heating or other emission processes. For a given pulsar, it cannot be assessed a priori which of these applies, so it can only be asserted that *either* $\delta\mu_{thr} \gtrsim \delta\mu_1$ *or* $\delta\mu_{thr} \lesssim \delta\mu_2$.

The parameters needed to estimate $\delta\mu_2$ are listed in Table 1. Since all of these pulsars are heavily absorbed at the low-energy end of the ROSAT energy band, 0.1 keV (which is of most interest for the present application, since the effective temperatures turn out to be quite low), it is important to have a good estimate of the column density of neutral hydrogen along the line of sight to the pulsar, N_{HI}, in order to infer the true luminosity from the observed counts.

The first group of (seven) pulsars is at medium to high Galactic latitudes, $|b| > 15°$, therefore a reasonable estimate of N_{HI} is given by the velocity-integrated 21 cm emission near the position of the pulsars, which yields the values given in Table 1. For all of these pulsars, this value is within a factor of 4 (and in three cases less than a factor of 1.15) of the "rule of thumb" $N_{HI} = 10 N_e$, where N_e is the electron column density inferred from the pulsar dispersion measure.

For the remaining four pulsars (with $|b| < 7°$), the 21 cm emission maps do not give meaningful estimates for N_{HI}, since much of the emission is expected to come from behind the pulsar, and much of it may be optically thick. Therefore, I rely on the rule of thumb mentioned in the previous paragraph for a crude estimate of N_{HI}.

Given the estimates for d and N_{HI}, and assuming a fiducial neutron star radius, $R = 10\,\mathrm{km}$, blackbody spectra were folded through the ROSAT position-sensitive proportional counter (PSPC) response function (Briel et al. 1994) and HI absorption in order to find the surface temperatures, T_{BB}, giving the correct count rates, and the corresponding ratios of bolometric luminosity to spin-down power, $L_{BB}/\dot{E}_{rot}$. For the two pulsars observed with ROSAT's high-resolution imager (HRI) rather than the PSPC, the counts were converted to equivalent PSPC counts by multiplying by a factor of 10, a rough, but reasonable estimate, given the similarity of the efficiency curves at low energies (Briel et al. 1994). From these results, one obtains the values of $\delta\mu_2$ given in Table 2. Relativistic effects were neglected throughout.

Of course, the assumption of blackbody spectra made above does not strictly apply. Realistic neutron star atmosphere calculations (Rajagopal & Romani 1996; Zavlin, Pavlov, & Shibanov 1996) yield spectra that depart substantially from a blackbody with the same effective temperature, in most cases by excess emission in the high-energy tail, compensated by a deficit at low energies. Since ROSAT only sees the high-energy tail, this effect adds to the possible presence of additional heat sources in the star and of additional emission processes around it to make the values obtained here overestimate the true effective temperature, luminosity, and $\delta\mu_2$. Thus, the constraints placed on the superfluid energy gaps by the values of $\delta\mu_2$ in Table 2 are weaker than those which would be obtained with a more complete and realistic model.

On the other hand, the main difficulty in estimating $\delta\mu_1$ is our nearly complete ignorance of the true pulsar age, t. Varying it in the range $0 < t < t_s$ makes $\delta\mu_1$ sweep from zero to infinity. Thus, as a very rough approximation, I took $t = t_s/2$, unless this turned out larger than the age of the Galactic disk, $\sim 9\,\mathrm{Gyr}$ (Liebert, Dahn, & Monet 1988, 1989), which is the case for pulsars J2322+2057 and J2019+2425. For these, I took $t = 9\,\mathrm{Gyr}$.

Better estimates of t should soon be available from the luminosities of some pulsars' white dwarf companions. At present, such estimates are uncertain and controversial (e.g., Lorimer et al. 1995; Alberts et al. 1996), and have therefore not been taken into account in this work. In addition, more accurate estimates of t will be hampered by the complicated evolutionary history of ms pulsars (e.g., Bhattacharya & van den Heuvel 1991). It is commonly believed that ms pulsars have been spun up by accretion from their binary companions. In this process, if the temperature does not increase enough to allow reactions to restore equilibrium, the core material will attain a

chemical imbalance opposite in sign to that resulting from spin-down, which will grow up to the threshold value, $-\delta\mu_{thr}$. Once mass transfer stops, the star starts spinning down. Now, this spin-down must first reduce the chemical imbalance to zero before it can start building it up with the opposite sign. Thus, from the end of the accretion phase until reactions resume, the star must lose twice as much rotational energy as would be the case if it had started in chemical equilibrium.

Figure 2 shows the allowed regions $\delta\mu_{thr} > \delta\mu_1$ and $\delta\mu_{thr} < \delta\mu_2$ as black horizontal lines, leaving the forbidden regions (if any) as blanks in between. Though individual values of $\delta\mu_1$ and $\delta\mu_2$ can hardly be trusted, this Figure shows that the current data are in fact starting to probe the interesting range $0.1\,\mathrm{MeV} \lesssim \delta\mu_{thr} \lesssim 1\,\mathrm{MeV}$. In particular, if energy gaps far above 1 MeV are considered to be excluded by theoretical considerations, then the combination of the 3 very fast pulsars, B1937+21, B1957+20, and B1821-24, seems to give a fairly safe constraint $\delta\mu_{thr} \lesssim 0.4\,\mathrm{MeV}$ (unless they are all much younger or intrinsically much brighter than assumed here).

4. Discussion

The results of the previous section, though far from conclusive in their present form, show that it might be possible in the near future to use the present scheme to put interesting constraints on the superfluid energy gaps in neutron star cores, assuming that all the assumptions made in the model are correct.

Substantial additional progress can be made along several lines:

1) The theoretical predictions will be made more precise by considering state-of-the-art neutron star models, their actual contraction due to spin-down, all particle species present, possibly relevant neutrino cooling mechanisms, and the effects of general relativity. Time dependence is likely to be irrelevant, and a steady-state model should be sufficient.

2) A detailed study of the interaction between the chemistry of the core and the crust along the lines discussed at the end of §2 should definitely be done. This would show whether reactions in the crust might provide a shortcut that prevents the growth of a substantial chemical imbalance in the core.

3) Deeper x-ray observations (with higher sensitivity and/or longer integration time) with better spectral resolution should allow to eliminate much of the

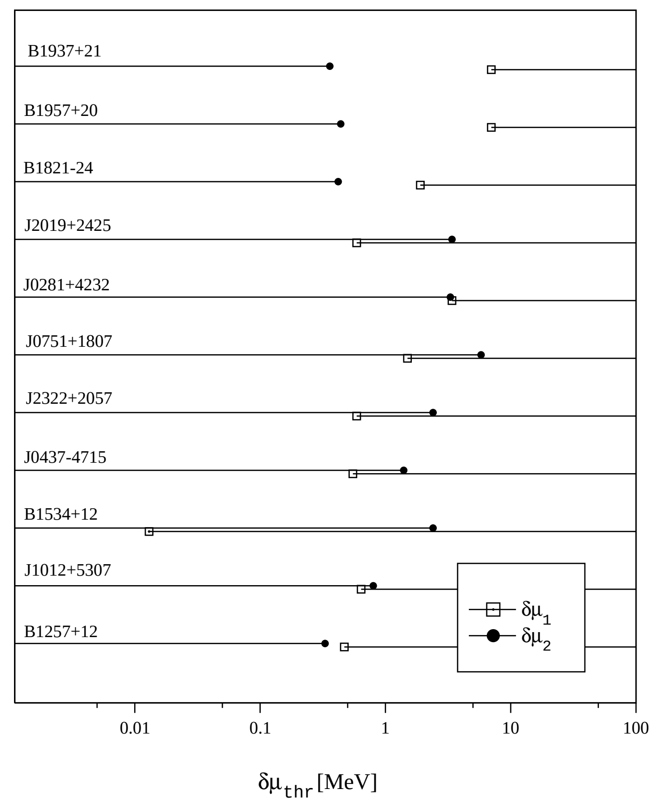

Fig. 2.— Constraints on the threshold chemical potential difference $\delta\mu_{thr}$ from preliminary analysis of ms pulsar data. For each pulsar, $\delta\mu_{thr} > \delta\mu_1$ or $\delta\mu_{thr} < \delta\mu_2$.

non-thermal contribution to the flux, setting tighter limits on the thermal portion and, perhaps, on the amount of absorbing neutral hydrogen along the line of sight.

4) The improved spectra should be fitted by realistic theoretical atmosphere models (Zavlin et al. 1996), rather than assuming blackbody spectra and constraining them with the total count rates.

5) Measurements of the absorption of pulsar radio flux in the 21 cm line of neutral hydrogen could improve the estimates of the absorbing column density.

6) An independent limit on the thermal flux might be obtained through optical observations of the Rayleigh-Jeans tail. The predicted fluxes are extremely low, and in many cases the neutron star may be fainter than its white dwarf companion, even in the B and U bands. However, single millisecond pulsars may be detectable with next-generation telescopes with long enough integration.

7) Improvements of white dwarf cooling calculations may provide more secure age determinations for ms pulsar-white dwarf binary systems. This would help in estimating the initial rotational energy of the pulsar, and therefore its expected chemical imbalance, $\delta\mu_1$.

This study has benefitted from information exchange with many colleagues, including A. Alpar, W. Becker, L. Bildsten, J. Halpern, K. Iida, M. Kiwi, P. Krastev, J. Miralda-Escudé, D. Page, G. Pavlov, M. Ruderman, J. Sauls, and V. Zavlin. I also thank J. Véliz for preparing the figures, and G. Reineking for help with the tables. This work was financially supported by FONDECYT (Chile) grant 1961134 and by a grant from Fundación Andes' "Program for the Insertion of Chilean Scientists."

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Table 1

Upper bounds on the blackbody emission of ms pulsars observed by ROSAT

Name	d [kpc]	$\log \dot{E}_{rot}$ [ergs s^{-1}]	R_{PSPC} [10^{-3}s^{-1}]	b [°]	N_{HI} [10^{20}cm^{-2}]	kT_{BB} [eV]	$L_{BB}/\dot{E}_{rot}$ [10^{-3}]	References
B1257+12	0.6	33.74	≤ 0.31	75	2.7	≤ 23	≤ 0.65	1, 2, 3
J1012+5307	0.5	33.50	≤ 5.5	51	0.75	≤ 25	≤ 1.6	4, 5, 6
B1534+12	0.7	33.28	≤ 1.0	48	3.6	≤ 29	≤ 4.7	1, 2, 3
J0437-4715	0.14	33.61	200.	-42	1.9	≤ 33	≤ 3.7	1, 2, 7, 8
J2322+2057	0.8	33.15	≤ 0.2	-37	4.7	≤ 27	≤ 4.8	1, 2, 3
J0751+1807	2	33.80	3.6	21	4	≤ 49	$\leq 12.$	9, 10
J0281+4232	5.7	35.40	(21)	-18	5	≤ 107	≤ 6.6	11, 12
J2019+2425	0.9	33.12	≤ 0.28	-6.6	5.3	≤ 29	≤ 6.8	1, 2
B1821-24	5.1	36.33	10.3	-5.6	37	≤ 109	≤ 0.84	1, 2
B1957+20	1.5	35.06	2.0	-4.7	9	≤ 53	≤ 0.87	1, 2
B1937+21	3.6	36.04	(≤ 6.6)	2.3	22	≤ 89	≤ 0.73	2, 12

Note.—Columns: 1. Pulsar name. 2. Adopted distance. 3. Logarithm of the spin-down power, assuming a moment of inertia $I = 10^{45}$g cm^2. 4. ROSAT PSPC count rate (numbers in parenthesis were inferred from HRI observations; see text). 5. Galactic latitude. 6. Adopted column density of neutral hydrogen along the line of sight to the pulsar. 7. Highest blackbody temperature of a spherical object of 10 km radius at the adopted distance compatible with the detected count rates (or upper limits) and the adopted HI column density. 8. Ratio of the blackbody luminosity to the spin-down energy. 9. References for the numbers in columns 1-6: (1) Danner et al. (1994); (2) Taylor et al. (1993); (3) Burstein & Heiles (1978); (4) Nicastro et al. (1995); (5) Lorimer et al. (1995); (6) Halpern (1996); (7) Bell et al. (1995); (8) Heiles & Cleary (1979); (9) Lundgren et al. (1995); (10) Becker et al. (1996); (11) Navarro et al. (1995); (12) Verbunt et al. (1996).

Table 2

Constraints on $\delta\mu_{thr}$ from ms pulsars observed by ROSAT

Name	P [ms]	t_s [Gyr]	$\delta\mu_1$ [MeV]	$\delta\mu_2$ [MeV]	References
B1257+12	6.2	3.2	0.47	0.33	1
J1012+5307	5.3	7	0.64	0.8	4, 5
B1534+12	37	0.2	0.013	2.4	1
J0437-4715	5.7	5	0.55	1.4	7
J2322+2057	4.8	21	0.59	2.4	1
J0751+1807	3.5	8.2	1.5	5.8	9
J0281+4232	2.3	0.5	3.4	3.3	11
J2019+2425	3.9	27	0.59	3.4	1
B1821-24	3.1	0.03	1.9	0.42	1
B1957+20	1.6	2.1	7.0	0.44	1
B1937+21	1.6	0.2	7.0	0.36	2

Note.—Columns: 1. Pulsar name. 2. Radio pulse period. 3. Characteristic (spin-down) age, $t_s = P/(2\dot{P})$. 4. $\delta\mu_1$ (defined in the text), as calculated from the data in columns 2 and 3. 5. $\delta\mu_2$ (defined in the text), as calculated from the data in Table 1. 6. References for the numbers in columns 2 and 3, as listed below Table 1.